Evaluating the structural and functional equivalency of natural and restored oyster reefs in the Rachel Carson Reserve

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Description

Statement of the Problem: Estuaries in eastern North America were once replete with the eastern oyster *Crassostrea virginica*, an iconic ecosystem engineer that fueled coastal economies for centuries. A suite of chronic stressors—including historic overharvesting [1,2], habitat degradation [3], sedimentation [4], and disease [5]—are largely responsible for remarkable oyster declines [2]. Losses in oyster reef habitat and biomass over the past century in eastern North America are estimated at 64% and 88%, respectively [6]. Coupled with these losses are the depreciation of ecosystem services oysters provide, including the provision of refugia from predators, feeding and nursery habitat, direct harvest value, biofiltration, nutrient reductions, and shoreline armoring [7,8]. Oyster restoration projects seek to recover these services [9].

Broadly, a major restoration goal is achieving equivalence in structure and function between natural and restored habitats [10]. While several direct assessments of aspects of these equivalencies exist for subtidal oyster reefs [11–15], they vary regionally and temporally. For example, one study in the Chesapeake Bay found that non-oyster faunal densities were significantly higher in restored plots than natural plots after 3-5 years [13]; another in Mississippi found constructed reefs surpassed natural reefs in oyster density, taxa richness, and faunal abundance after only 2 years. Fewer studies have considered the structural and functional equivalencies of intertidal oyster reefs. A study in South Carolina suggested that the faunal composition of constructed reefs was less diverse than natural reefs after 7 years, but did not examine reef structure [11]. In North Carolina, Theuerkauf [16] and Brodeaur [17] suggested that conserving natural intertidal reefs should be a management priority because they host more abundant oyster populations than hardened shorelines. Whereas community composition assessments are absent from those studies, Keller [18] included oyster populations *and* associated fauna and found few differences between constructed and natural salt marsh-fringing reefs after 2 years.

North Carolina boasts a rich and recent history of both sub- and intertidal oyster restoration research [16–26]. But given the aforementioned studies' divergent findings, a more comprehensive examination of the equivalencies between natural and restored oyster reefs is clearly merited. **Reefs built over the past 2+ decades in the Rachel Carson Reserve** [21,22,26] **offer a rare opportunity to compare attributes of restored intertidal oyster reefs of varying ages to natural reference reefs. A longitudinal study that quantifies oyster restoration trajectories may clarify if and when restored intertidal reefs meet—or even surpass—natural reefs in structure and function, as well as the maximum restoration potential of oyster habitat in the North Carolina Coastal Reserve, National Estuarine Research Reserve System (NERRS), and beyond.**

Background: Highly variable success criteria further complicate the evaluation of oyster reef restoration. Compared to other coastal biogenic habitats, oyster reefs are unique in that, until lately, their restoration initially focused on augmenting fisheries loss, and thus success criteria primarily reflected fisheries-based metrics such as abundance of market-sized (>75mm) oysters

[27]. More recently, Baggett et al. [28] recommended four universal restoration performance criteria regarding physical and population structure: reef areal dimensions, reef height, oyster density, and oyster size-frequency distribution. However, success criteria that evaluate the community function of restored oyster reefs are equally critical for a holistic evaluation of their performance. Previous studies have used benthic macrofaunal (i.e., prey resource), juvenile fish, and piscivorous fish (i.e., predator) composition through time as a metric for assessing community functional equivalence [13,14,26].

From 1997-2016, scientists at the University of North Carolina Institute of Marine Sciences (IMS) built a substantial number of experimental oyster reefs in and around the Rachel Carson Reserve to answer a multitude of ecological and biogeochemical research questions. Importantly, these studies have determined that a vertical 'hotspot' exists for oyster biomass accumulation between -0.5 and -0.6 m NAVD88 [21], and that restored reefs on mud flats support higher oyster biomass and faunal densities than those adjacent to seagrass beds and salt marshes [26,29]. I propose to return to sites on mudflats between -0.5 and -0.6 m NAVD88—the landscape conditions under which these experimental reefs have historically performed best—that are 3, 8, 19, and 22 years old.

The objectives of this research are to quantify and evaluate the structural and functional attributes of natural reference and restored intertidal oyster reefs of various ages, and estimate the time required for the restored reefs to reach structural and functional equivalency with or outperform natural reefs. Long-term oyster restoration trajectories are not well-studied, nor are they included in the NERRS System-Wide Monitoring Program (SWMP). Thus, this research directly addresses a number of the Coastal Reserve's coastal management research priorities, namely the **evaluation of oyster habitat restoration practices and subsequent ecosystem services they may deliver.** Specifically, I hope to combine the results of this and previous studies [18,21,26,29] to recommend restoration efforts that most efficiently maximize recovery and a return-on-investment. Further, the data I collect will also be a **critical first 'snapshot' of these oyster reefs' conditions post-Hurricane Florence**, and may serve as an important reference point for future studies as threats of dramatic environmental change and increased frequency and severity of extreme events continue to loom.

Aims, Hypotheses, and Methods

Proposed natural reference reefs and restored reefs are located on sand/mud flats surrounding Middle Marsh (Table 1). I selected the restored reefs based on a similarity of planting elevations (range = -0.500 to -0.660 m; mean = -0.538 m), and will ensure that the selected natural reference reef sites are at comparable elevations at the study's commencement. Sampling will occur from April—October 2019 (Table 2).

Aim 1: Measure and compare the physical reef and oyster demographic structures—change in reef area and height, oyster density, biomass, size-frequency distribution, and growth rates and survival—of natural reference and restored oyster reefs. For restored reefs, estimate time-to-structural-equivalence to reference reefs.

- H_{a1}: Physical reef traits are positively and logistically correlated with reef age and depth. Oyster demographic structures are significantly different between reefs of different ages, and these demographic structures converge with or outperform natural reefs ~3 years after their establishment.

Method: I will survey reef height using a Trimble GPS, and measure reef dimensions to estimate reef area. To determine oyster densities and size-frequency distributions, I will hand excavate n = 2 randomly placed 0.25 m^2 quadrats, then weigh excavated contents and measure, and sort oysters into 1-cm length bins [19]. I will perform the excavation methods in late April and early October to bookend the primary oyster spawning periods. Methods for quantifying growth rates and survival are adapted from Puckett and Eggleston [20]. Briefly, I will build and deploy a settlement tray near the top of each reef (n = 15) in early May. Each month through October, I will randomly mark up to n = 20 individuals with numbered Betterbee® queen bee tags before digitally photographing the trays and measuring both the newly and previously marked individuals with digital calipers. The tags will allow me to track the lengths and fate of individuals in each monthly 'settlement cohort' and calculate survivorship through time.

Table 1. Plant dates, elevations, and locations of reefs proposed to sample.

Plant year	Elevation (m)	Lat.	Long.	ID, previous study	ID, this study	Age in 2019	Citation
1997	-0.500	34.6937	-76.6198	MF1_97	97_01	22	Grabowski, 2005
1997	-0.660	34.6929	-76.6221	MF2_97	97_02	22	Grabowski, 2005
1997	-0.517	34.6850	-76.6125	MF4_97	97_03	22	Grabowski, 2005
2000	-0.500	34.6930	-76.6202	MF1_00	00_01	19	Grabowski, 2002
2000	-0.553	34.6927	-76.6208	MF2_00	00_02	19	Grabowski, 2002
2000	-0.522	34.6852	-76.6121	MF4_00	00_03	19	Grabowski, 2002
2011	-0.515	34.6978	-76.6144	1S5	11_01	8	Fodrie et al., 2014
2011	-0.591	34.6885	-76.6200	2L6	11_02	8	Fodrie et al., 2014
2011	-0.513	34.6849	-76.6099	4L5	11_03	8	Fodrie et al., 2014
2016	-0.509	34.6877	-76.6186	CCA5	16_01	3	unpublished
2016	-0.508	34.6882	-76.6192	CCA7	16_02	3	unpublished
2016	-0.567	34.6847	-76.6114	CCA16	16_03	3	unpublished
natural	TBD	34.6965	-76.6343	NA	NR_01	unknown	NA
natural	TBD	34.69793	-76.6314	NA	NR_02	unknown	NA
natural	TBD	34.69072	-76.6200	NA	NR_03	unknown	NA

Aim 2: Quantitatively assess and compare the community assemblage and functional diversity of natural reference and restored oyster reefs. Estimate restored reefs' time-to-functional-equivalence to reference reefs.

- H_{a2}: Functional group density, biomass, and diversity are positively and logistically correlated with reef age and depth; restored reefs reach functional equivalence to or surpass natural reefs ~3 years post-planting.

Method: The following methods adapted from Grabowski [26] and Rodney and Paynter [13] to quantify prey resources, juvenile fish, and piscivorous fish (i.e., predators). I will sample for prey resources during the quadrat sampling outlined in Aim 1. Specifically, I will first subsample a 15 cm core each plot down to 10 cm for polychaetes, amphipods, and other infauna. Then, I will identify, count, and measure the free-living invertebrate macrofauna and epifauna within the rest of the excavated quadrate material. To assess juvenile fish abundance patterns, I will deploy n = 2 minnow traps at each reef for ~6 hours between midflood and midebb tide each month from May through October around the full moon. During those deployments, I will also place n = 1 (10 m × 1.5 m, with 7.5 cm slit openings) gill net at each reef to quantify piscivorous fish. Upon trap and net collection, I will measure, count, and identify the organisms captured in the minnow traps and gill nets to species; I will also weigh the piscivorous fish. Further, I will assign each organism to one of four functional feeding groups [11]: deep deposit feeders, surface deposit feeders, suspension feeders, and carnivores/omnivores.

Statistical Analysis: Following the recommendation of Walters and Coen [11], I will test the above hypotheses using permutation tests for multivariate analysis of similarity (PERMANOVA, R package 'vegan'). The authors compared a number of classical and non-parametric analytic approaches for comparing natural and restored oyster reefs and deemed the

PERMANOVA approach as the most flexible and powerful. Provided the expectation that restored reefs will rapidly reach accretion equilibrium with sea level [25], that I do not have historical reef height data for the natural reefs will not limit this project.

Table 2. Tasks and timeline.

Task	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Oyster quadrat excavation	X						X		
Survey physical reef structure		X							
Sample oyster demographic structure		X	X	X	X	X	X		
Assess fish abundances		X	X	X	X	X	X		
Analyze data, write report							X	X	X

Outreach and Dissemination

Applying an understanding of how restored oyster reefs recover the structure and function of natural reefs through time will inform project trajectory expectations of future restoration projects in North Carolina. Thus, the findings from this study will be of considerable value to the agencies charged with planning and managing such projects, including: NC Coastal Federation, NC Divisions of Marine Fisheries and Coastal Management, The Nature Conservancy, and NOAA/NC Sea Grant. Additionally, I plan to present this research at the 2020 Benthic Ecology Meeting (BEM) in Wilmington. To support the development of young researchers and diversification of the scientific community, I will mentor and fund an undergraduate at the same rate as National Science Foundation Research Experience for Undergraduate programs, as well as fund their travel to and attendance at BEM (Table 3).

Core to my personal research philosophy is the inclusion and engagement of individuals outside of academia in the scientific process. I have demonstrated a commitment to this ideal prior to and within graduate school as the citizen science educator at the Port Townsend Marine Science Center (WA) and teaching fellow at the Charleston Marine Life Center (OR). Drawing upon my background in K-12 Next Generation Science Standards-aligned curriculum design, I will co-develop a unit on oyster reefs with teachers at Beaufort and Morehead City Middle Schools. The unit will fulfill "MS-LS2: Ecosystems: Interactions, Energy, and Dynamics" learning objectives, and I will share it with other local educators at Scientific Research and Education Network (SciREN) events. Moreover, I will continue to participate in the Skype a Scientist match program that fosters communication between scientists with classrooms across the nation. Provided my extensive experiences in oyster research and science education and communication, I am uniquely qualified to conduct this study and associated outreach.

Budget and Other Sponsored Support

Table 3. Budget and other sponsored support.

Expense	Cost ($)
Nikon COOLPIX W300 rugged + waterproof camera ($400/camera × 1)	400
128 GB microSD memory card ($20/card × 2)	40
Betterbee® queen bee marking kit ($30/kit × 5)	150
Misc. field gear (buckets, gill netting + repair supplies, oyster bags + baskets, PVC pipe)	500
Boat + truck gas (50 days @ [5 + 1 gallons]/day × est. $3/gal)	900
Boat fee (50 days @ $30/day)	1500
Undergraduate researcher ($12.5/ hr @ 40 hrs/week for 11 weeks)	5500
Conference registration for Knorek + undergraduate researcher ($200/per student × 2)	400
Travel to conference + hotel for Knorek + undergraduate researcher ($300/per student × 2)	600
Total	**$9,990**
Sponsored support	
Research assistantship ($23,000 + tuition)	
Access to minnow traps, Trimble GPS, additional field supplies	

Data Management Plan

The North Carolina Coastal Reserve-North Carolia Sea Grant project "Evaluating the structural and functional equivalency of natural and restored oyster reefs in the Rachel Carson Reserve" by Zofia Knorek (and Joel Fodrie, Niels Lindquist) will generate environmental data, including physical oyster habitat characteristics (reef area and height, oyster density, and biomass). This project will also generate oyster demographic data (size-frequency distributions, growth rates, and survivorship) and oyster reef community composition data (functional group density, biomass, and diversity). We will determine reef height using a Trimble GPS, aerial dimensions using field measuring tapes per Rodriguez et al. [20], and oyster densities, biomasses, and demographic data using methods outlined in Puckett and Eggleston [22]. Further, we will use Grabowski's [26] and Walters and Coen's [11] methods for assessing faunal composition. After recording data in field notebooks, we will scan, save, and transcribe the data into Microsoft Excel spreadsheets for storage an analysis, which we will save on the Institute of Marine Sciences Server and the UNC Fish Ecology Lab Dropbox. Data collection is expected to start on 1 April 2019 and end on 31 October 2019, though deviations may occur as a consequence of imcliment weather or shared equipment (i.e., boat and truck) scheduling constraints. All data will be available to the Lab and interested collaborators upon request; please contact Zofia Knorek at zofia@unc.edu for more information or to make a data request. Once we have analyzed the data, we plan to publish our findings in peer-reviewed scientific journals within 2 years following the completion of data collection. Following the initial publications of these data, we will share them with the NERRS SWMP for use in future longitudinal reef monitoring studies. Our project personnel will continue disseminate our findings about the predicted trajectories of oyster habitat restoration in NC via local outreach events. The PIS have a reliable record of positing their work and experimental media on the internet through the IMS and personal webpages.

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30 November 2018

Dr. Brandon Puckett
Coastal Reserve Research Coordinator
North Carolina Coastal Reserve and National Estuarine Research Reserve
North Carolina Division of Coastal Management

Dear Dr. Puckett,

It is my pleasure to submit this letter of support for the NC Coastal Research Fellowship application of Ms. Zofia Knorek. Since joining our lab group this year, she has launched herself into oyster-reef research, with a dual focus on boing sponge dynamics and the efficacy of restoration techniques/efforts. She spent most of the summer exploring North Carolina oyster reefs, and throughout the fall has begun to explore a large-scale dataset on the distribution and abundance of boring sponge in and around the NC Oyster Spawning Sanctuaries.

The study Zofia proposes herein combines previously ground-truthed methods to provide a novel longitudinal evaluation of oyster restoration trajectories in the Rachel Carson Reserve. In addition to building a number of the experimental oyster reefs Zofia plans to revisit, our lab group has explored an array of their ecological and biogeochemical functions. We also have a reliable publication record documenting these projects. Zofia recognized a data gap in our understanding of how these restored reefs have developed through longer timescales. Most parallel field studies that track restored intertidal oyster reefs are 1) conducted a shorter period post-restoration (i.e., 2-5 years) and/or 2) evaluate only their structural *or* functional equivalencies to natural reefs. Cleverly and opportunistically, Zofia has devised a comprehensive yet reasonable sampling regime for reefs that are 3, 8, 19, and 22 years-old—and compares both their structural *and* functional metrics to natural reefs. Provided the ubiquitous perils of oyster habitats throughout the NERR system and absence of biological monitoring of oyster reefs in the System-Wide Monitoring Program (SWMP), the data Zofia collects may lend critical insight to maximizing restoration potential throughout the system. And given that her proposal is a natural extension to our previous work, I clearly have a vested interest in seeing it come to fruition.

Zofia began her PhD in my lab group this fall after completing her MS at the University of Oregon; I am co-advising her with Dr. Niels Lindquist. In her short tenure as our student, she has demonstrated her aptitude for and efficiently analyzing the body of oyster restoration literature, identifying knowledge gaps, and independently generating clear and original proposals that address applied oyster ecology issues. Zofia's master's thesis also centered on oysters, and thus she has a practiced record of successfully conducting oyster research. We are confident in Zofia's ability to complete the proposed work, and look forward to supporting her in her pursuit.

Thank you for your consideration of this letter and Zofia's proposal.

Sincerely,

Joel Fodrie
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Zofia Knorek, Curriculum Vitae

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Education

2018 – Present	**University of North Carolina at Chapel Hill**. *Chapel Hill, NC.* PhD Student in Ecology. Advisors: F. Joel Fodrie and Niels Lindquist.
2016 – 2018	**University of Oregon, Oregon Institute of Marine Biology**. *Charleston, OR*. Master of Science in Biology. Advisor: Aaron Galloway. GPA: 3.96.
2011 – 2015	**Hendrix College**. *Conway, AR.* Bachelor of Arts in Biology with Distinction, *Cum Laude.* GPA: 3.77.

Research Experience

2018 –	**Spatiotemporal dynamics of salinity, boring sponge and oyster populations in restored North Carolina oyster sanctuaries.** University of North Carolina at Chapel Hill Institute of Marine Sciences.
2016 – 2018	**A tale of two tunicates: *Didemnum vexillum* and *Botrylloides violaceus* as biofouling agents in bivalve aquaculture.** Oregon Institute of Marine Biology.
2015 – 2016	**Citizen science research: Puget Sound Seabird Survey, SoundToxins, Harbor Porpoise Monitoring, Sea Star Wasting Monitoring, etc**. *Citizen Science Educator AmeriCorps*. Port Townsend Marine Science Center.
2015	**Characterizing the diaphragm of deep-diving beaked whales (*Mesoplodon* spp.).** Hendrix College.
2014	**A multifaceted, highly resolved investigation into the trophic role of small pelagic fishes on the Northeast US Continental Shelf**. Woods Hole Oceanographic Institution.
2013	**Microbial diversity in restored urban and natural freshwater habitats in Central Arkansas: A foundation for a research-based curriculum**. Hendrix College.

Fellowships and Grants

2018	**University of North Carolina at Chapel Hill Doctoral Merit Fellowship** ($53,032)
2017	**Dr. Nancy Foster National Oceanographic and Atmospheric Administration Scholarship** (Top 15 National Finalist)
2017	**National Science Foundation Graduate Research Fellowship** (Honorable Mention)
2016 – 2018	**University of Oregon Graduate Fellowship** ($4,797 per quarter + tuition voucher)
2016	**Segal AmeriCorps Education Award** ($5,795)
2016	**National Science Foundation Graduate Research Fellowship** (Honorable Mention)
2011 – 2015	**Hendrix College Provost's Scholarship** ($135,720)
2014	**Watson Fellowship** (National Finalist)
2014	**Hendrix College Odyssey Research Grant** ($4,505)
2014	**National Science Foundation Maryland Sea Grant Research Experience for Undergraduates** ($6,000; declined to work at WHOI)

Publications

Knorek, Z.R. 2018. A tale of two tunicates: *Didemnum vexillum* and *Botrylloides violaceus* as biofouling agents in bivalve aquaculture. University of Oregon. Master's Thesis: http://hdl.handle.net/1794/23754

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Presentations

Knorek, Z.R. and Hansen, B. Seasonal dynamics of a *Didemnum vexillum* population in Oregon: A five-year summary. American Academy of Underwater Sciences Symposium, Granlibakken Resort, Tahoe City, CA. October 2018.

Suca, J. J., Pringle, J.W., **Knorek, Z.R.**, Richardson, D. E., Llopiz, J.K. Feeding dynamics of Northwest Atlantic small pelagic fishes. Ocean Sciences Meeting, Oregon Convention Center, Portland, OR. February 2018.

Knorek, Z.R. Invasion of land and sea: Cause and effect. Pub Science Invited Talk, Seven Devils Brewery, Coos Bay, OR. May 2017.

Knorek, Z.R., Whitford, L.N, and Carlson, E.P. Ocean Acidification Study Through Systems and Inquiry Science. Western Society of Naturalists, Hyatt Regency, Monterey, CA. November 2016.

J.K. Llopiz, J. Pringle, **Z.R. Knorek.** A multifaceted, highly resolved investigation into the trophic role of small pelagic fishes on the Northeast US Continental Shelf. American Fisheries Society, Oregon Convention Center, Portland, OR. August 2015.

Teaching

2018	**Conservation Biology,** University of Oregon, *Teaching Assistant*
2017, 2018	**Marine Conservation Biology,** Oregon Institute of Marine Biology, University of Oregon, *Teaching Assistant*
2017	**Marine Environmental Issues,** Oregon Institute of Marine Biology, University of Oregon, *Teaching Assistant*
2017	**Charleston Marine Life Center,** Oregon Institute of Marine Biology, University of Oregon, *Graduate Teaching Fellow*
2016	**NOAA Bay and Watershed Education Training Program**, *Instructor*
2015 – 2016	**K-12 Programming**, Port Townsend Marine Science Center, *Instructor*
2014 – 2015	**Biology Writing Center**, Hendrix College, *Assistant*
2013 – 2015	**Zoology**, Hendrix College, *Tutor, Teaching Assistant*
2014	**Marine Biology**, Hendrix College, *Teaching Assistant*

Biographical Sketch

Fredrick Joel Fodrie
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A. Professional Preparation

University of North Carolina at Chapel Hill	Biology (Highest Honors) and History	(B.A.) 1999
Scripps Institution of Oceanography (UCSD)	Biological Oceanography	(Ph.D.) 2006
Dauphin Island Sea Lab (Alabama)	Post-Doctoral Researcher (Fisheries)	2006-2008

B. Appointments

2016-	Associate Professor, Institute of Marine Sciences & Department of Marine Sciences, University of North Carolina at Chapel Hill, Morehead City, NC
2009-2016	Assistant Professor, Institute of Marine Sciences & Department of Marine Sciences, University of North Carolina at Chapel Hill, Morehead City, NC
2008-2009	Research Assistant Professor, Dauphin Island Sea Lab & Department of Marine Sciences, University of South Alabama, Mobile, AL

C. Publications

(i) 5 products closely related to the proposed project (out of 66). *Mentored: [$]postdoctoral researcher; [#]graduate student; [*]undergraduate/technician.*

Ziegler[#], SL, **FJ Fodrie**, CJ Baillie[*], and JH Grabowski (2018) Effects of landscape setting on oyster reef structure and function persist more than a decade post restoration. Restoration Ecology **26**: 933-942.

Fodrie, FJ, AB Rodriguez, RK Gittman, JH Grabowski, NL Lindquist, CH Peterson, MF Piehler, and JT Ridge[#] (2017) Oyster reefs as carbon sources and sinks. *Proceedings of the Royal Society B, Biological Sciences **284**: 20170891*.

Walles, B, **FJ Fodrie**, S Nieuwhof, PMJ Herman, and T Ysebaert (2016) Guidelines for evaluating performance of oyster habitat restoration should include tidal emersion: reply to Baggett et al. Restoration Ecology **24**: 4-7.

Fodrie, FJ, AB Rodriguez, CJ Baillie[*], MC Brodeur[#], SE Coleman[#], RK Gittman, DA Keller[#], MD Kenworthy, AK Poray, JT Ridge[#], EJ Theuerkauf, and NL Lindquist (2014) Classic paradigms in a novel environment: inserting food-web and productivity lessons from rocky shores and saltmarshes in to biogenic reef restoration. Journal of Applied Ecology **51**: 1314-1325.

Rodriguez, AB, **FJ Fodrie**, JT Ridge[#], NL Lindquist, EJ Theuerkauf, SE Coleman[#], JH Grabowski, MC Brodeur[#], RK Gittman, DA Keller[#], and MD Kenworthy (2014) Oyster reefs can outpace sea-level rise. Nature Climate Change **4**: 493-497.

(ii) 5 other products

Kroll[#], IR, AK Poray, BJ Puckett, DB Eggleston, and **FJ Fodrie** (2018) Quantifying estuarine-scale invertebrate larval dispersal and connectivity: methodological and ecological insights. Limnology and Oceanography **63**: 1979-1991.

Ridge[#], JT, AB Rodriguez, and **FJ Fodrie** (2017) Evidence of exceptional shellfish reef resilience to rapid fluctuations in sea level. Ecology and Evolution **7:** 10409-10420.

Ridge[#], JT, AB Rodriguez, and **FJ Fodrie** (2017) Saltmarsh and fringing oyster reef transgression in a shallow temperate estuary: implications for restoration, conservation and blue carbon. Estuaries and Coasts **40**: 1013–1027.

Keller[#] DA, RK Gittman, R Bouchillon[*], and **FJ Fodrie** (2017) Life stage and species identity determine whether habitat subsidies enhance or simply redistribute consumer biomass. Journal of Animal Ecology **86**: 1394-1403.

Ridge[#], JT, AB Rodriguez, **FJ Fodrie**, NL Lindquist, MC Brodeur[#], SE Coleman[#], JH Grabowski, and EJ Theuerkauf (2015) Maximizing oyster-reef growth supports green infrastructure with accelerating sea-level rise. Scientific Reports **5**: 14785.

D. Synergistic Activities

2018	Lead PI and Author: "North Carolina Strategic Plan for Shellfish Mariculture: a vision to 2030"; Report to the North Carolina General Assembly
2016	Faculty Host/Manager: North Carolina Blue Heron Bowl and National Ocean Sciences Bowl
2015-	Proposal Panelist: Maryland Sea Grant Core Funding Panelist (2017; 1 of 4 members); Connecticut Sea Grant Core Funding Panelist (2017; 1 of 6 members); National Science Foundation Biological Oceanography Panelist (2017; 1 of 13 members) California Sea Grant Core Funding Panelist (2015-present; 1 of 6 recurring members) National Science Foundation Graduate Research Fellowship Program Panelist (2015)
2014-2017	North Carolina Site PI: Zostera Experimental Network (zenscience.org),
2013-	Member: North Carolina Division of Marine Fisheries, Habitat and Water Quality Advisory Committee

Niels Lyle Lindquist – Oyster Focused Biographical Sketch

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Morehead City, North Carolina 28557
phone - (252) 726-6841 ext. 136, email - nlindquist@unc.edu

A. Professional Preparation

1992-1993	U.S. DOE Global Change Distinguished Postdoctoral Fellow, Institute of Marine Sciences, University of North Carolina at Chapel Hill
1989-1991	NSF Postdoctoral Fellow in Marine Biotechnology and the Ocean Sciences, Institute of Marine Sciences, University of North Carolina at Chapel Hill
1989	Ph.D. in Oceanography, University of California, San Diego, Scripps Institution of Oceanography
1983	B.S. in Chemistry, University of Florida, Gainesville, Florida

B. Professional Positions

2002	Professor, University of North Carolina at Chapel Hill, Institute of Marine Sciences and the Department of Marine Sciences
1998	Associate Professor, University of North Carolina at Chapel Hill, Department of Marine Sciences and the Institute of Marine Sciences
1997	Visiting Associate Professor, University of North Carolina at Chapel Hill, Department of Marine Sciences and the Institute of Marine Sciences
1993-1997	Research Assistant Professor, University of North Carolina at Chapel Hill, Curriculum in Marine Sciences and the Institute of Marine Sciences

C. Publications

5 publications most closely related to the proposed research

Fodrie, FJ, AB Rodriguez, RK Gittman, JH Grabowski, NL Lindquist, CH Peterson, MF Piehler, and JT Ridge (2017) Oyster reefs as carbon sources and sinks. *Proceedings of the Royal Society B, Biological Sciences 284: 20170891*.

Ridge, JT, AB Rodriguez, FJ Fodrie, NL Lindquist, MC Brodeur, SE Coleman, JH Grabowski and EJ Theuerkauf. 2015. Maximizing oyster-reef growth supports green infrastructure with accelerating sea-level rise. *Scientific Reports* 5; Article number 14785; doi:10.1038/srep14785

Fodrie, FJ, AB Rodriguez, CJ Baillie, MC Brodeur, SE Coleman, RK Gittman, DA Keller, MD Kenworthy, AK Poray, JT Ridge, EJ Theuerkauf and NL Lindquist. 2014. Classic paradigms in a novel environment: inserting food web and productivity lessons from rocky shores and saltmarshes into biogenic reef restoration. *Journal of Applied Ecology* 51:1314-1325.

Rodriguez, AB, FJ Fodrie, JT Ridge, NL Lindquist, EJ Theuerkauf, SE Coleman, JH Grabowski, MC Brodeur, RK Gittman, DA Keller and MD Kenworthy. 2014. Oyster reefs can outpace sea-level rise. *Nature Climate Change* 4:493-497.

Robert P. Dunn, R. P., D. B. Eggleston and N. Lindquist. 2014. Oyster-sponge interactions and bioerosion of reef-building substrate materials: implications for oyster restoration. *Journal of Shellfish Research* **33**:727-738.

5 other recent publications

Jean-Luc Mouget, J-L, C François, V Demoulin, J-S Deschenes, N Lindquist, P Lejeune, C Audet, G Hallegraeff, P Cormier, A Seger, R Tremblay, T François, C Falaise, S Gobert and D Sirjacobs. Harmful or harmless: biological effects of marennine on marine organisms. *Journal of Aquatic Toxicology* (in review)

Hoer, D, J Tommerdahl, N Lindquist and CS Martens. 2018. Dissolved inorganic nitrogen fluxes from common Florida Bay (USA) sponges. *Limnology & Oceanography* **63**:2563-2578, (DOI) - 10.1002/lno.10960

Hoer, DR, PJ Gibson, JP Tommerdahl, NL Lindquist and CS Martens. 2018. Consumption of dissolved organic carbon by Caribbean reef sponges. *Limnology & Oceanography* 63:337-351, doi.org/10.1002/lno.10634

Robert P. Dunn, R. P., D. B. Eggleston and N. Lindquist. 2014. Effects of substrate type on demographic rates of eastern oyster (*Crassostrea virginica*). *Journal of Shellfish Research* **33**:177-185.

Gloeckner, V, Wehrl, L Moitinho-Silve, C Gernert, P Schupp, JR Pawlik, NL Lindquist, D Erpenbeck, G Worheide and U Hentschel. 2014. The HMA-LMA dichotomy revisited: an electron microscopical survey of 56 sponge species. *Biological Bulletin* **227**:78-88.

D. Synergistic Activities

Oyster Relevant Databases Created

SalWise - a comprehensive North Carolina salinity database to facilitate management and Restoration of critical fish habitats. Created by N Lindquist and S Fegley development funded by the NC DMF, Coastal Recreational Fishing License Program.

Pending Patent Applications Under Examination

Ephemeral Oyster Substrates for Oyster Aquaculture (PCT/US2016/020966; WO 2016144786 A1), N. Lindquist and D. “Clammerhead” Cessna co-inventors, UNC Chapel Hill patent owner; Patent rights licensed to Sandbar Oyster Company Inc.

Companies Created

Sandbar Oyster Company Inc incorporated August 2014 as the entity to license the patent rights for the novel UNC biodegradable hardscape for oyster aquaculture, habitat restoration and living shoreline creation.

Awards

2017 Finalist, FISH 2.0 Global Business Impact Challenge, Stanford University, Stanford, California, November 7-9, 2017

2017 Rural Entrepreneurs of the Year - awarded by the North Carolina Rural Economic Development Center to N Lindquist and D "Clammerhead" Cessna as co-founders and leaders of Sandbar Oyster Company.

2016 NC IDEA Foundation, Startup Competition Award Winners, N Lindquist and D “Clammerhead” Cessna – Sandbar Oyster Company ($50,000).

Public Service (oyster-related)

2018-present, Member, Newport River (NC) Water Quality Improvement Workgroup

2018-present, Member, APNEP Living Shoreline Steering Committee

2017-present, Member, NC Shellfish Mariculture Advisory Committee

2015-present, Member, North Carolina Oyster Steering Committee

2015-2016, Member, NC Division of Marine Fisheries Hard Clam and Oyster Fisheries Management Plan Advisory Committee

2014-present, Member, Northeast Oyster Working Group, organized by the North Carolina Coastal Federation